Turbocharger Characteristics Analysis of 93 kW Marine Diesel Engine

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***Abstract*— Along with the developments of the maritime world, ship demand with the appropriate performance increase. At this time the ship with the size of 30 GT being crowded discussed. The way to improved it performance can be done from various aspects, one of it is by installed a turbocharger. The first step taken was to collect data specifications of the marine diesel engine. Performance predictions obtained by modeling the engine in simuation software. Simulation covers the entire engine from the dimensions, air flow in-out, fuel injection systems, etc. Engine performance predictions is done by installation of three turbocharger with different specifications. The simulation process was made into several cases based on the engine rotation 800, 1000, 1200, 1400, 1500, 1600, 1700, 1800, 1900, 2000, 2200 RPM. Simulation by software is made to obtained the characteristics of engine performance such as torque, power, fuel consumption, pressure, etc. Turbochargers used in the simulation are GT2052-3, GT2052-1, and GT1241. Highest brake power generated by the engine installed with GT2052-3 turbocharger is 129.824 HP with 61.4% compressor efficiency. Brake power engine installed with GT2052-1 turbocharger generated power for 125.549 HP with 73.9% compressor efficiency. Brake power engine installed with GT1241 generated power for 71.172 HP with 47.4% compressor efficiency.**

***Keyword*— Marine Diesel Engine, Performance, Matching, Turbocharger, Simulation, Modeling**

I. INTRODUCTION

Indonesia is the world's largest archipelago country with more than 17,000 islands. This is one of a potential source of enormous latent power to be developed. Maritime and fisheries sector is very necessary role to increase the economic growth which aims to improve the welfare of people, including fisherman and their families. The country has a vast 5.8 million km^2 Exclusive Economic Zone, as well as 81,000 km of maritime borders. The sea therefore holds considerable potential, on which a large part of the population depends. There are currently some 6 million Indonesian fishermen and fish farmers and 15 to 20% of the country's population rely on the fisheries sector for their livelihood.

At this time, there are a lot of fishing vessels are currently under development in Indonesia. One of them which is under development are fishing vessels with a size of 30 Gross Tonnage. Development is carried out for fishing vessel is divided into a several aspects, the development of the vessel include; design, economical, and performance. In terms of performance improvement on a fishing vessel can be performed at the engine sector. Such improvements can be done by installation of turbocharger to the engine of the vessel. This improvement aim to increase the engine performance by maximized the power output and efficiency of the engine it self.

II. LITERATURE REVIEW

A. *Turbocharger Working Principle*

A turbocharger is basically an air pump. Hot exhaust gases leaving the engine after combustion are routed directly to the turbine wheel side of the turbocharger to make it rotate. That turbine wheel is connected by a shaft to a compressor wheel. As the turbine wheel spins faster and faster, it causes the compressor wheel to also spin quickly. The rotation of the compressor wheel pulls in ambient air and compresses it before pumping it into the engine's chambers.

As it guessed, the compressed air leaving the compressor wheel housing is very hot as a result of both compression and friction. So what's needed is a way to cool that air down before it enters the chambers. That's where a charge-air cooler (or "heat exchanger") comes in. It reduces the temperature of the compressed air so that it is denser when it enters the chamber (heat causes things to expand, as we all learned in science class). The charge-air cooler also helps to keep the temperature down in the combustion chamber. All together, the engine, turbocharger and charge-air cooler form what is known as a "charge-air system".

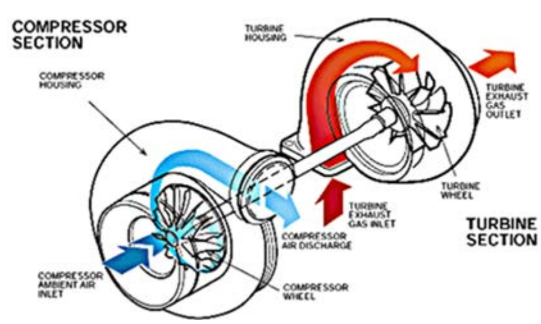


Figure 1 Turbocharger structure and components

B. *Exhaust Gas Operation Method*

In constant pressure type turbocharger, the exhaust gases gets collected in a single exhaust gas reservoir, where the pressure is maintained constant so as to avoid any fluctuation in the exhaust gas energy pressure. The exhaust gas is introduced to the turbine side after maintaining the pressure inside the cylinder. Exhaust gas with constant pressure type allows for the concetration of all cylinder gas output, so as the result of such things make air mass flow fluctutations, low pressure in the manifold and relatively constant (Turbo Magazine I: 1993).

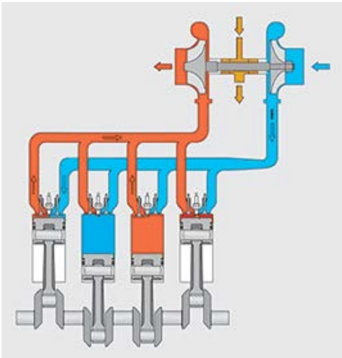


Figure 2 Constant pressure exhaust gas

In pulse type turbocharger, the exhaust gas directly enters the turbine side and drives the turbine with the exhaust gas energy. The connection from the exhaust side of an engine is directly connected to the turbine side of a turbo charger. The pipe connections from the exhaust gas towards the turbine side are generally small in length and exhaust grouping is provided to prevent the blowback of gases from one cylinder to another.

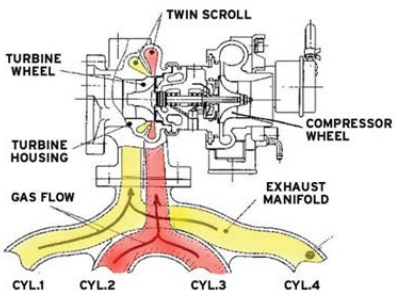


Figure 3 Steps in Fault Tree Analysis

C. Compressor

Turbocharger compressors are generally centrifugal compressors consisting of three essential components: compressor wheel (inducer dan impeller), rotor, compressor shaft, diffuser, silencer – filter, air intake casing, and housing. With the rotational speed of the wheel, air is drawn in axially, accelerated to high velocity and then expelled in a radial direction (Hamid Keshaverzi: 2005)

The compressor operating behaviour is generally defined by maps showing the relationship between pressure ratio and volume or mass flow rate. The useable section of the map relating to centrifugal compressors is limited by the surge and choke lines and the maximum permissible compressor speed.

D. Turbine

The turbocharger turbine, which consists of a turbine wheel and a turbine housing, converts the engine exhaust gas into mechanical energy to drive the compressor. The gas, which is restricted by the turbine's flow cross-sectional area, results in a pressure and temperature drop between the inlet and outlet. This pressure drop is converted by the turbine into kinetic energy to drive the turbine wheel.

There are two main turbine types: axial and radial flow. In the axial-flow type, flow through the wheel is only in the axial direction. In radial-flow turbines, gas inflow is centripetal, i.e. in a radial direction from the outside in, and gas outflow in an axial direction.

The turbine performance increases as the pressure drop between the inlet and outlet increases, i.e. when more exhaust gas is dammed upstream of the turbine as a result of a higher engine speed, or in the case of an exhaust gas temperature rise due to higher exhaust gas energy.

E. Turbocharger Efficiency

The compression process in the compressor is a polytropic process with increasing entropy due to friction and losses in the compressor. Figure 3 shows the compression process of the intake air from the state 1 at the compressor inlet (p1, T1) to state 2 at the compressor outlet (p2, T2). The compressor efficiency ηC is defined as the ratio of the isentropic total enthalpy change from 1t to 2st to the polytropic total enthalpy change from 1t to 2t. In other words, the compressor needs more energy in the polytropic process (real process) than the possibly minimal required energy of the compressor stage in the isentropic process (ideal process). (Baines, Japikse, et al: 2005-1988-1994)

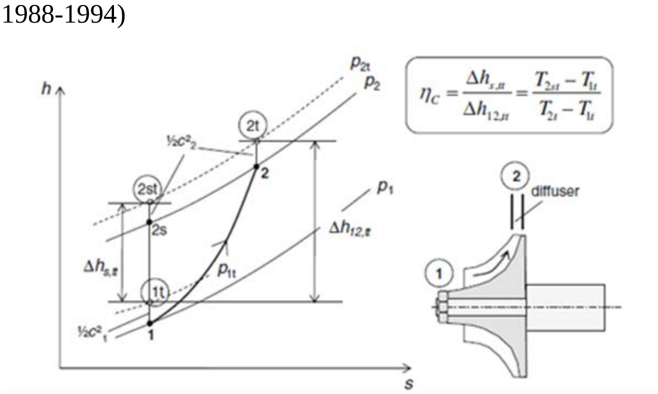


Figure 4 Compression process in the compressor stage in h-s diagram

The total–total isentropic efficiency of the compressor stage (further called compressor) consisting of the compressor wheel and diffuser is defined as

$$\eta_C = \frac{\Delta h_{s,tt}}{\Delta h_{12,tt}} = \frac{T_{2st} - T_{1t}}{T_{2t} - T_{1t}} \ldots (1)$$

The total–total isentropic efficiency is generally used in the compressor since the kinetic energy of gas in the state 2 could be transformed into the pressure energy in the diffuser. The process increases the charge-air pressure. Using thermodynamic equations for the isentropic process, the compressor efficiency is written in terms of the total pressures and temperatures at the inlet and outlet of the compressor, and the isentropic exponent of the charge air κa ≈ 1.4.

$$\eta_C = \frac{\left(\frac{p_{2t}}{p_{1t}}\right)^{\left(\frac{\kappa-1}{\kappa}\right)_a} - 1}{\left(\frac{T_{2t}}{T_{1t}}\right) - 1} \ldots (2)$$

The compressor efficiency is determined by measuring the total pressures and temperatures at the inlet and outlet of the compressor according to Eq. (2). The maximum total–total isentropic efficiency of the compressor ηC is normally between 70 and 80 % at the design point in the compressor performance map. Analogous to the compressor, the efficiency of turbine results from the polytropic expansion process of the exhaust gas from the state 3 at the turbine inlet (p3, T3) to state 4 at the turbine outlet (p4, T4), see Fig. 4 The turbine efficiency ηT is defined as the ratio of the polytropic total enthalpy change from 3t to 4t to the isentropic total enthalpy change from 3t to 4s. Physically speaking, the turbine delivers less output energy due to friction and losses in the polytropic expansion process than the possibly maximum energy given in the isentropic process.

III. RESEARCH METHODOLOGY

Research on this paper will be do by simulation modeling the specific engine using simulation software. Simulation modeling used to analuzed the performance of the engine installed with three types of turbocharger. First step to identify the specification of the engine such as, dimension, air flow, cylinder number, etc. After finished on engine identification step for all system, the next step is modeling an engine into a simulation software to obtained the performance of basic engine. After that is selecting turbocharger with a various specification to be installed on the engine. After modeling an engine with the specific turbocharger, performance of each engine installed with a different turbocharger compared. The best efficiency of turbocharger will be selected for the engine.

IV. DISCUSSION AND RESULTS

A. Engine Specificatian Data Used

Simulation done by marine diesel engine which has been design in previous study. The following is a specification of the engine data will be used in the simulation.

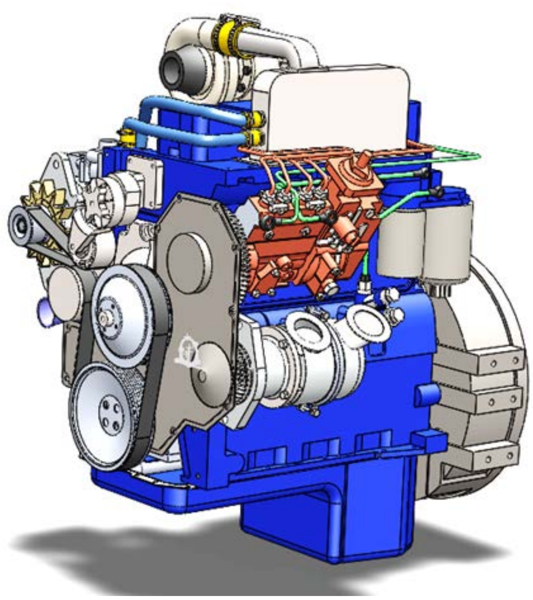


Figure 5 Designed engine by Juniono Raharjo, 2015

Table 1 Engine specification

4- Stroke	Linear Engine
Cylinder Number	4
Displacement	3.9 Litre
Bore	102 mm
Stroke	120 mm
Inlet Valve	44 mm
Outlet Valve	43 mm
Compression Ratio	16.5
Firing Order	1-3-4-2

From the simulation process, simulator generates a multiple output file containing simulation results in a various format. The result output will be used for performance analysis of the engine. At the end of simulation process, report that summarizes the simulation result can be made. This report contain the important information about simulation and simulation results in the form of graph and table.

The simulation will be conducted in several different cases. The installation of three different turbocharger will be done in simulation process. This simulation process will run at speeds 800, 1000, 1200, 1400, 1600, 1700, 1800, 2000, 2200. From the simulation result will be analyzed to know the details on engine characteristic performance based on turbocharger installation.

B. Turbocharger I (GT2052-3)

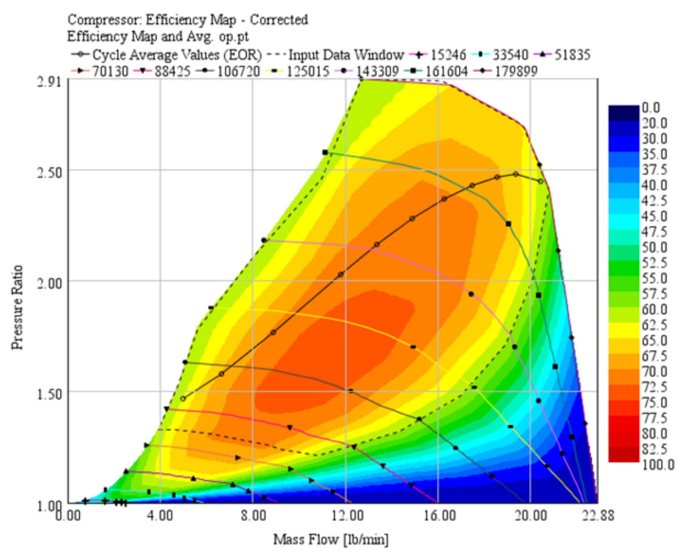


Figure 6 Operating line turbocharger – engine GT2052-3

From the figure above shown the operating line of turbocharger compressor to the engine. Operating line turbocharger compressor to the engine data is used to prove the installation of the turbocharger on the specific engine is appropriate, in the sense that is no surge and stall . Surging is the complete breakdown of steady through flow, affecting the whole machine, in other words, when stalling takes place on all the blades simultaneously. This leads to choking of the flow. The color from compressor map shows the efficiency area of the compressor it self. At the 2200 RPM pressure ratio result is 2.447 bar, compressor outlet pressure 2.335 bar, compressor outlet temperature 437.356 K, mass flow rate 19.598 lb/min, and compressor efficiency at 61.413%.

C. Turbocharger II (GT2052-1)

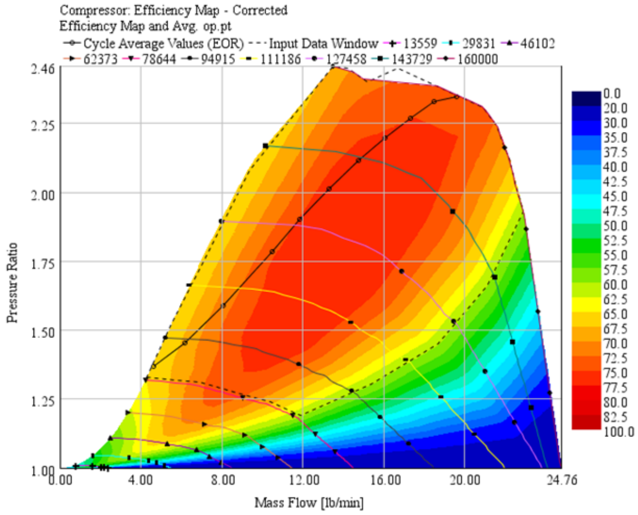


Figure 7 Operating line turbocharger – engine GT2052-1

From the figure above shown the operating line of turbocharger compressor to the engine. Operating line turbocharger compressor to the engine data is used to prove the installation of the turbocharger on the specific engine is appropriate, in the sense that is no surge and stall . Surging is the complete breakdown of steady through flow, affecting the whole machine, in other words, when stalling takes place on all the blades simultaneously. This leads to choking of the flow. The color from compressor map shows the efficiency area of the compressor it self. At the 2200 RPM pressure ratio result is 2.376 bar, compressor outlet pressure 2.247 bar, compressor outlet temperature 408.01 K, mass flow rate 18.847 lb/min, and compressor efficiency at 73.933%.

D. Turbocharger – Engine Matching Comparation GT1241

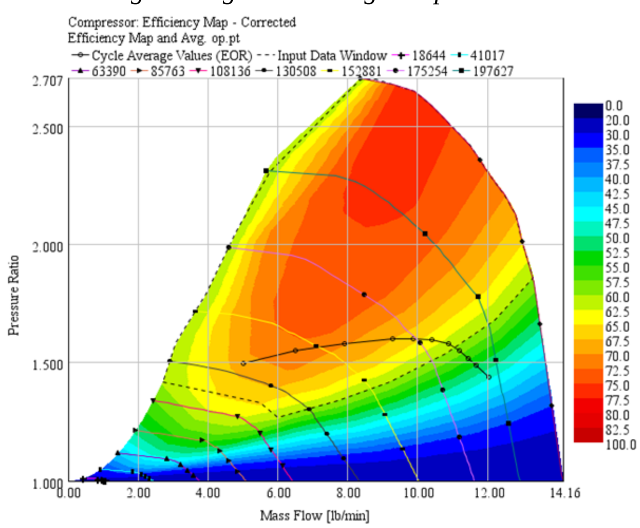


Figure 8 Operating line turbocharger – engine GT1241

Surging is the complete breakdown of steady through flow, affecting the whole machine, in other words, when stalling takes place on all the blades simultaneously. This leads to choking of the flow. The operating line of turbocharger compressor above is exceeded the choke line of compressor map. The choke line is typically defined by the point where the efficiency drops below 58%. In addition to the rapid drop of compressor efficiency past this point, the turbo speed will also be approaching or exceeding the allowable limit. The color from compressor map shows the efficiency area of the compressor it self. The line exceeded compressor map at 1700 RPM. At the 2200 RPM pressure ratio result is 1.426 bar, compressor outlet pressure 1.377 bar, compressor outlet temperature 364.767 K, mass flow rate 12.04 lb/min, and compressor efficiency at 47.444%.

E. Turbocharger – Engine Matching Comparation GT2052-3

Table **2** Output turbocharger GT2052-3

Type of Device	Compressor	Turbine
Speed [RPM]	178662	178662
Pressure Ratio (static)	2.48	2.48
Pressure Ratio	2.45	2.54
Mass Flow Rate [kg/s]	0.15	0.15
Power [kW]	21.1	23.6
Efficiency [%]	61.4	72.1
Inlet Pressure [bar]	0.94	3.01
Outlet Pressure [bar]	2.34	1.21
Inlet Temperature [K]	297	898
Outlet Temperature [K]	437	766
Map PR Exceeded/Stalled ?	NO	NO
PR less than 1.0 ?	NO	NO

Table **3** Output turbocharger GT2052-3

RPM	Brake Power (kW)	SFOC (g/kWh)	TORQUE (Nm)
2200	96.823	228.023	420.269

Based on the trendline performance output on GT2502-3 compressor and turbine map obtained the data output as shown above. Table above is the output results of engine performance to turbocharger at 100% load. Turbocharger shaft speed is 178662 RPM at maximum load. Turbocharger compressor generates power by 21.1 kW , and turbine by 23.6 kW. Average efficiency engine performance to turbocharger is 61.4%, with turbine efficiency 72.1%. The power generated at 2200 RPM of the engine is 96.823 kW. Fuel consumptios used by 228.023 g/kWh, with torque value of 420.629 Nm. From trendline performance output on turbocharger compressor map, the trendline position looks to be in the middle of the map. But as it shows the trendline tend to be closer to the surge line with the top of trend line almost approach the boundary of the choke line. Based on theory of turbochargers and turbocharging, ideal trendline operation is located in a region that is almost approaching the surge line with efficiency level turbocharger >80%.

F. Turbocharger – Engine Matching Comparation GT2052-1

Table **4** Output turbocharger GT2052-3

Type of Device	Compressor	Turbine
Type of Device	Compressor	Turbine
Speed [RPM]	165365	165365
Pressure Ratio (static)	2.38	2.41
Pressure Ratio	2.35	2.46
Mass Flow Rate [kg/s]	0.14	0.15
Power [kW]	16	22.1
Efficiency [%]	73.9	72
Inlet Pressure [bar]	0.95	2.89

Outlet Pressure [bar]	2.25	1.2
Inlet Temperature [K]	297	896
Outlet Temperature [K]	408	768
Map PR Exceeded/Stalled ?	NO	NO

Table 5 Output turbocharger GT2052-1

RPM	Brake Power (kW)	SFOC (g/kWh)	TORQUE (Nm)
2200	93.622	228.489	406.374

Based on the trendline performance output on GT2502-1 compressor and turbine map obtained the data output as shown above. Table above is the output results of engine performance to turbocharger at 100% load. Turbocharger shaft speed is 165365 RPM at maximum load. Turbocharger compressor generates power by 16 kW, and turbine by 22.1 kW. Average efficiency engine performance to turbocharger is 73.9%, with turbine efficiency 72%. The power generated at 2200 RPM of the engine is 93.622 kW. Fuel consumptios used by 228.489 g/kWh, with torque value of 406.374 Nm. From trendline performance output on turbocharger compressor map, the trendline position looks to be in the middle of the map. But as it shows the trendline tend to be closer to the surge line. Based on theory of turbochargers and turbocharging, ideal trendline operation is located in a region that is almost approaching the surge line with efficiency level turbocharger >80%.

G. *Turbocharger III (GT1241)*

Table 6 Output turbocharger GT1241

Type of Device	Compressor	Turbine
Speed [RPM]	194046	194046
Pressure Ratio (static)	1.43	1.82
Pressure Ratio	1.44	1.85
Mass Flow Rate [kg/s]	0.09	0.09
Power [kW]	6.2	8.9
Efficiency [%]	47.4	67.7
Inlet Pressure [bar]	0.97	1.97
Outlet Pressure [bar]	1.38	1.08
Inlet Temperature [K]	298	879
Outlet Temperature [K]	365	793
Map PR Exceeded/Stalled ?	NO	NO
PR less than 1.0 ?	NO	NO

Table 7 Output turbocharger GT1241

RPM	Brake Power (kW)	SFOC (g/kWh)	TORQUE (Nm)
2200	51.929	254.828	225.401

Based on the trendline performance output on GT1241 compressor and turbine map obtained the data output as shown above. Table above is the output results of engine performance to turbocharger at 100% load. Turbocharger shaft speed is 194046 RPM at maximum load. Turbocharger compressor generates power by 6.2 kW , and turbine by 8.9 kW. Average efficiency engine performance to turbocharger is 47.4%, with turbine efficiency 67.7%. The power generated at 2200 RPM of the engine is 51.929 kW. Fuel consumptios used by 254.828 g/kWh, with torque value of 225.401 Nm. From trendline performance output on turbocharger compressor map, the trendline position looks linear from the midle of the map to the area outside the choke line. Based on theory of turbochargers and turbocharging, ideal trendline operation is located in a region that is almost approaching the surge line with efficiency level turbocharger >80%.

H. *Specific Fuel Oil Consumption Comparison*

Evaluated from the existing results of engine specific fuel oil consumption, there are difference in basic engine specification and engine installed with turbocharger.

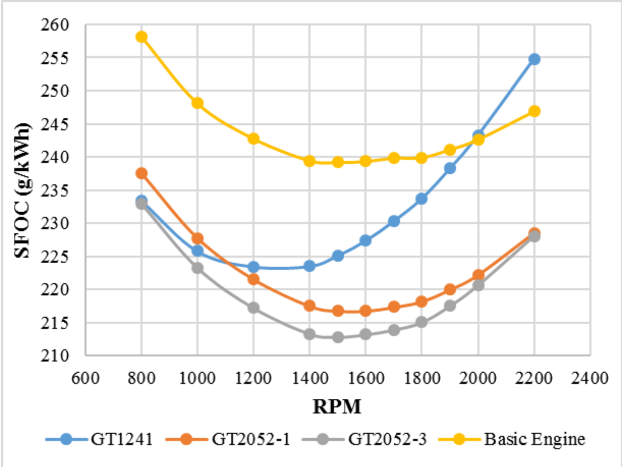
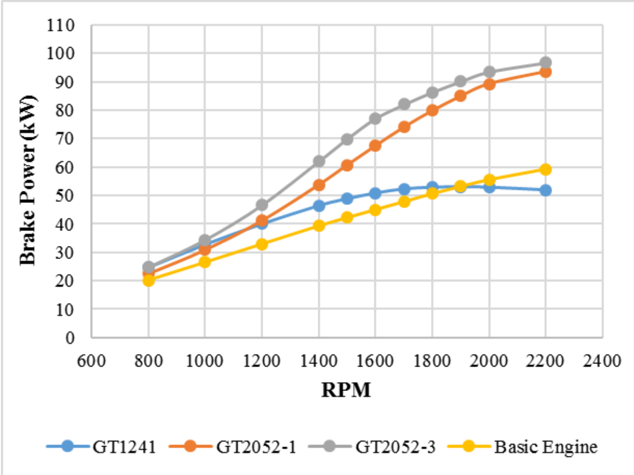


Figure 9 SFOC Comparison

From the graph above shown the line of engine specific fuel oil consumption. The yellow line is the line of basic engine fuel consumption without any turbocharger. And another color of the line shows the engine fuel consumption installed by different turbocharger specification. From the graph above the lowest fuel consumption shown in gray line with GT2052-3 turbocharger installed. The value obtained is 212.806 g/kWh at 1500 RPM.

I. *Brake Power in kW Comparison*

Evaluated from the existing results of engine brake power, there are difference in basic engine specification and engine installed with turbocharger.

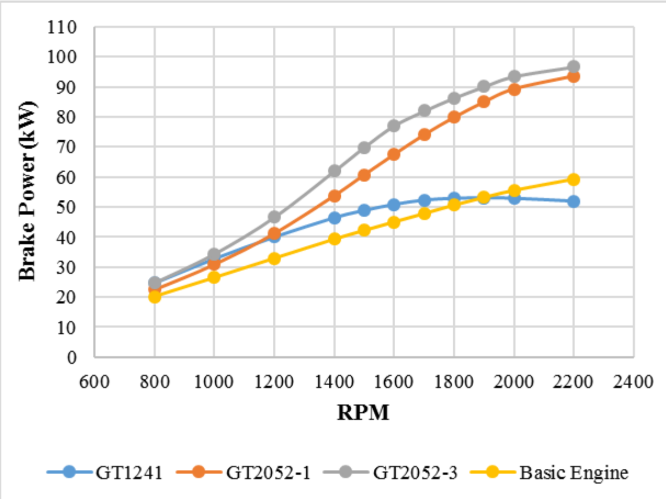


Brake Power (kW) Comparison

From the graph above shown the line of engine brake power in kW. The yellow line is the line of basic engine brake power without any turbocharger. And another color of the line shows the engine brake power installed by different turbocharger specification. From the graph above the highest power generated shown in gray line with GT2052-3 turbocharger installed. The value obtained is 96.823 kw at 2200 RPM.

J. Brake Torque Comparison

Evaluated from the existing results of engine brake torque, there are difference in basic engine specification and engine installed with turbocharger.



Graph 4.12 Brake Torque Comparison

From the graph above shown the line of engine brake torque. The yellow line is the line of basic engine brake power without any turbocharger. And another color of the line shows the engine brake torque installed by different turbocharger specification. From the graph above the highest torque generated shown in gray line with GT2052-3 turbocharger installed. The value obtained is 460.761 Nm at 1700 RPM.

V. CONCLUSION

Based on the simulation results analysis that has been done, obtain some conclusions, among others:

1. Turbocharger match results known from operating line turbocharger to the engine performance. From the first turbocharger (GT2052-3), maximum power output value is 96.823 kW at 2200 RPM. Obtained torque value by 420.269 Nm, with a specific fuel oil consumption by 228.02 g/kWh. The second turbocharger (GT2052-1), maximum power output value is 93.622 kW at 2200 RPM. Obtained torque value by 406.374 Nm, with a specific fuel oil consumption by 228.389 g/kWh. The third turbocharger (GT1241), maximum power output value is 51.929 kW at 2200 RPM. Obtained torque value by 225.401 Nm, with a specific fuel oil consumption by 254.828 g/kWh. So turbocharger selected for the main engine is GT2502-3 with lowest SFOC, highest power, and highest torque generated.
2. Maximum load of the engine at 2200 RPM installed with GT2502-3 turbocharger, power generated value is 96.823 kW. Efficiency of the selected turbocharger compressor map is 61.4%, and turbine efficiency map 72%. Compressor and turbine revolution is at 178662 RPM. Boost pressure generated at highest point of this turbocharger used is 2.379 bar, with a temperature of 431.306 K.

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